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**A method for making decisions**  
**in complex problems**

by

**Marvin L. Manheim and Fred L. Hall**

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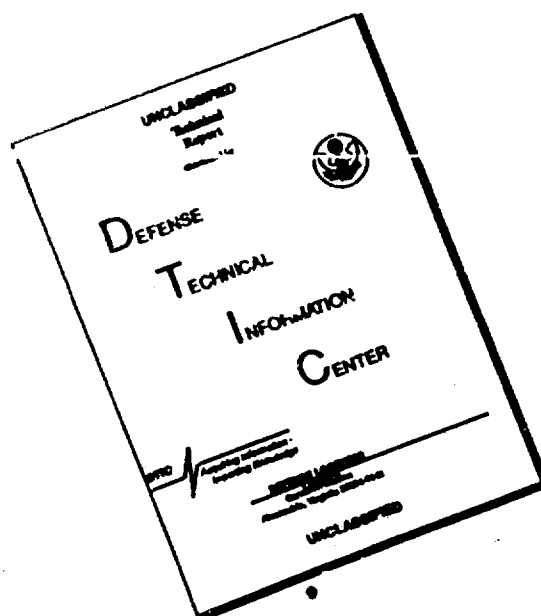
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PROFESSIONAL PAPER P67-24

DEPARTMENT OF CIVIL ENGINEERING

ABSTRACT REPRESENTATION OF GOALS

A method for making decisions in complex problems

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## ABSTRACT

This paper presents a method for choosing among alternatives in complex, multi-goal problems. The method consists of four principal steps. First, list all the known goals. Second, determine how the various goals are related--specification, means-end, value-wise independent or dependent. Third, determine which goals can be predicted, and obtain predictions on them. Fourth, use any of five techniques to condense this predicted data through several stages into a final choice. The method operates on paired alternatives to produce a preference; it can be applied sequentially to all the alternatives to produce a complete preference ranking.

## I. EXPLANATION OF THE METHOD

### Definition of the Problem

One of the main problems facing transportation planners and designers is that of choosing among several possible alternatives (1).<sup>1</sup> If we assume that the transportation designers can produce several feasible alternatives, then this problem of choice is the principal one remaining to be overcome. It is a problem which exists at many levels of planning, from choosing the type of surfacing for a road, to choosing a transportation system for the Northeast Corridor.

This problem of choice is greatly complicated by the fact that there are many complex and varied goals for transportation. Were there but one or two goals, choice would be reasonably simple. However, this is not at present the case: we wish not only to construct rapid, safe, efficient transportation facilities at low cost, but also to achieve social and economic objectives at the same time. We are concerned with measuring the effect of transportation investments on the rate and pattern of economic growth, and with finding the impacts on different social classes of various alternative transportation systems. Some of these goals, such as low cost, are traditional, but others are recent additions to the list, and because they are new, there is no reliable technique for considering them in choice.

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<sup>1</sup>Numbers in parentheses refer to entries in the bibliography at the end of the paper.

The problem dealt with here, then, is that of producing a method for choice that will enable us to consider the new goals as well as the traditional, and that leaves open the possibility of adding more goals. The input for this method is to be a list of the possible alternatives, plus whatever information is available from any single decision-maker (DM) about his preferences. (This information will be sketchy at best.) The output is to be a preference ranking of the alternatives.

#### Requirements for a Solution

In developing this model, there were several requirements we wished to meet:

- (1) The method has to be able to deal systematically with multiple goals, both quantifiable (e.g., cost) and non-quantifiable (e.g., aesthetics).
- (2) It has to be able to work with incomplete information about the relative values to the DM of the different goals.
- (3) It should be possible for the DM to participate extensively in the decision process, or for the method to utilize data on previous choices to operate semi-automatically, turning to the DM only when additional preference data is needed.
- (4) It should not force any more quantification upon the DM than is necessary to make a choice; especially in the semi-automatic operation, care should be taken to keep the mathematics at a minimal level, to keep the method close to the reasoning of the DM.

- (5) It should clarify, not obfuscate, the issues of choice (e. g., by noting what trade-offs are implied by certain decisions), and should point out these issues to the DM.
- (6) It must be dynamic, able to reflect changing values on the part of the DM, or encompass additional goals as they are discovered.
- (7) The method should provide an objective report of what is largely a subjective procedure, so that the logic of a decision can be seen by a second party, even though he disagrees with specific preferences leading to the decision.

#### Rejected Approaches to the Problem of Choice

Two approaches were tested and rejected in the process of arriving at the final method: cost-benefit analysis (and related approaches such as cost-effectiveness) and utility theory. Cost-benefit (2, 3) was rejected for two main reasons: it does not consider multiple goals but instead groups everything into two categories (cost and benefits); and it requires too much quantification--the DM must place a dollar value on each benefit in order to compare the benefits with the costs. Also, this process of quantifying the benefits contains the essence of the decision,<sup>2</sup> but this is not made clear; the procedure does not clarify the issues in the particular problem.

Utility theory (4, 5) is a method that attempts to place a



measure of value (utility) on all possible combinations of points on the goals, so that the problem of choice is made simple: note how each alternative fulfills the goals, read the utility for that combination of points and choose the one with the highest utility. This approach was rejected on roughly the same counts that cost-benefit was: it does not work well with multiple goals (there have been but a few attempts to construct a multi-dimensional utility, and these have all been highly mathematic and theoretical (6, 7); it requires too much precision--the DM must be able to supply information about his preferences over all possible combinations of points on the goals; and it tends to obfuscate the issues of choice by concealing them in the mathematics of utility. In addition, utility theory is not dynamic; a change in a valuation, or the addition of a goal, would require recalculation from the beginning of all the utilities.

#### The Resulting Method

The method constructed in response to the seven requirements stated above has two principal parts. The first is called the goal fabric analysis, and consists of listing all the known goals for the project and then identifying the various relations among the goals. The second is the procedure utilizing the goal fabric analysis to rank the alternatives. This entails mapping each new alternative

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<sup>2</sup>E. g., if the costs barely outweigh the benefits. then a change of a few dollars in valuing one of the benefits could have changed the decision; the decision was made when the benefit was given a dollar value.

onto the goal fabric (i. e. , predicting the performance of the alternative with respect to some of the goals) and then, using this mapped information and the structure of the goal fabric, comparing the new alternative with one previously ranked, to fit the new one into the ranking. The method operates on only two alternatives at a time.

Any attempt to formulate a list of goals runs into problems of consistency, overlap and varying degrees of detail of the goals. These problems are usually approached by trying to state all the goals in a uniform way. In the method we propose, however, this is precisely what is not done: the list of goals can contain overlap and different degrees of detail. We propose analyzing the list to identify explicitly all the relations among these "non-uniform" goals.

The goal analysis is intended to structure the goals by identifying the relations among them that are relevant to evaluation of the alternatives.<sup>3</sup> There are four relations of importance: specification, means-end, value-wise dependence, and value-wise independence.

The first two relations are used to guide expansion of the goals list in order to clarify the vague, general statements that usually

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<sup>3</sup> It is important to note that we are dealing only with evaluational relations. For example, it will probably not be relevant for evaluation that the out-of-pocket cost to the user of the facility is usually causally related to the costs of construction and operation. To put it another way, we wish to discover what relations among the goals are implied by the DM's method of using them in choice, not by physical causality.

<sup>4</sup> For examples of these vague statements, see References 8 and 9.

constitute goals.<sup>4</sup> Specification entails explaining in more detail what we mean by the general goal. For example, the goals "low fatalities" and "low injuries" are specifications of the general goal "safety".

The means-end relation describes how a goal can be accomplished (10). In this case the means goal is important only because it is instrumental to achieving the end. This end can in turn be a means to another goal, forming a means-end chain up to the intrinsic goals, the ones important in themselves. A means to the specified goals above might be to decrease the probability of accident; a means to the goal of decreasing fatalities would be to increase the speed of medical response.

Value-wise dependent goals are those that can be evaluated only in conjunction with other goals. An example of this could be in "safety": if fatalities are very low, we may be willing to accept more injuries than we would if fatalities were higher. Value-wise independent goals, on the other hand, can be evaluated on their own, without regard to any other goals.<sup>5</sup>

Once these goal relations have been established and listed, they provide a framework for condensing the huge mass of data that will be available into a reasonable number of categories. The relations and goals can be sorted through to produce a hierarchical tree-type structure (or perhaps a semi-lattice, an interwoven tree (12, 13) ) with the

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<sup>5</sup> For further elaboration of these ideas, see Reference 11, especially Chapter 9.

general goals on top, proceeding down through the specifics and the means-end chains to the lowest-level goals, those for which we can predict and measure the performance of the alternatives.<sup>6</sup>

Mapping an alternative onto the goal fabric entails predicting the performance of that alternative with respect to some of the goals. Prediction will probably entail the use of systems of models and other sophisticated techniques; however, the difficulties involved in prediction are beyond the scope of this paper. In mapping the alternative onto the goal fabric it is important to make certain that performance has been predicted on all necessary goals.

The final step uses the hierarchical structure of the goal fabric to conduct a dominance check between a newly mapped alternative and one that has previously been evaluated. The basic idea here is to consider subsets of goals, all of which are means to, or specifications of, the same goal. If there is dominance over the set, we can transfer the dominance to the more general goal; if there is not, we have somehow to combine and trade off goals to determine which alternative dominates. The value-wise independence or dependence information is useful at this point in the evaluation. This final step in the method will be explained in more detail in the example.

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<sup>6</sup>There is a hypothesis, as yet neither proved nor disproved, that the measurable goals will prove to be the lowest level of the specification relations. It is not easy to obtain measures for the means-end chains below this level.

## II. A HYPOTHETICAL EXAMPLE DEMONSTRATING THE METHOD

Using the method in a simple problem will probably do more to clarify the procedures than could quite a bit more explanation. To this end, we have worked out the following hypothetical problem, simplifying it so that the method will be clear. In addition, the data used are in most cases only rough estimates. Thus the example exists solely to illustrate the method, not to attempt a definitive solution to the problem.

### Definition of the Example Problem

The problem is to supply a passenger transportation system to serve the 1980 needs of the Northeast Corridor, with the first terminals to be in Boston, New York, Philadelphia and Washington, D. C., and the option to build others later in Hartford, New Haven, Baltimore and Richmond. The two alternatives to be decided between are a high-speed surface rail system built largely on existing right-of-way, and a VTOL (vertical take-off and landing) aircraft system.

The five goal or impact areas considered are: (1) convenience to the user, (2) safety, (3) aesthetics, (4) dollar cost, and (5) socio-economic impacts. Obviously, there are other important considerations, such as the adaptability of the system, but for easier comprehension we have limited the number of goals considered in this example.

The example illustrates the way the method is used to choose between two alternatives. The same procedure will have to be repeated several times when there is a larger number of alternatives; the method operates on only two alternatives at a time.

### Applying the Method

The first two steps are the listing and analysis of the goals. The basis for these was explained in the first section. Starting with general goals as found in this problem, the procedure is to expand the list and determine the specification and means-end relations by asking such questions as, "What do we mean by that goal?" "How can we accomplish this?" "What have these goals in common?" The expanded list is ordered, and then examined subjectively for the value-wise dependence or independence of related goals. (There is as yet no foolproof technique for determining this, although there probably should be.) The results of the goals analysis for this problem are shown in Figure 1 and 2.

The third and fourth steps use the goal fabric of Figures 1 and 2 to choose between rail and VTOL. The third step is to determine which goals can be predicted and measured with some accuracy and to obtain the predictions. These will not always be the lowest-level goals, but there must be a predictable goal in every branch of the tree--if there is one at a high level none are necessary below it.<sup>7</sup> If there is a branch of goals that cannot be predicted, they must be deleted (until prediction is possible): if we can obtain no data on a goal, it cannot enter the decision. Figure 3 lists the predictable goals, and the predictions for the two alternatives with respect to each goal.

The last part of this step is to convert the predicted data into preference information on each goal. This entails deciding which alternative is preferred on that goal and, if possible, the degree to which it is preferred, measured in any of several possible ways. Figure 4 is a representation of the goal fabric.<sup>8</sup> Those boxes containing a letter are the predictable goals; the letter indicates which alternative is preferred with respect to that goal: R is rail; Vis VTOL; = means the two are equally preferred.

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<sup>7</sup>Or, there can be some below which are used to predict at greater levels of detail: preliminary estimates would use higher-level predictable goals than would the final decision (14).

<sup>8</sup>Due to space limitations, the names of the goals are omitted in Figure 4. They can be determined by comparing the figure with Figures 1 and 2.

The information obtained to this point consists of the following: preference information; value-wise dependence and independence information; data already accumulated about the DM's preference on each goal and among different goals; and additional preferences asked of the DM for this particular problem (when necessary or desired).

The fourth step uses this information to move up one level in the goal fabric, from the predictable goals to the next level of goals. There are roughly five techniques that can be used to condense the data. All the techniques operate to give information on one higher-level goal at a time, working with those goals which comprise the higher one (e.g., "non-user aesthetics" is comprised of "noise" and "visual" aspects). The five techniques are described below as they are used in the example.

- (1) Dominance: the same alternative is preferred on all the goals comprising the new one; hence that same alternative is preferred on the new goal. The goal "non-user aesthetics" has VTOL preferred on both "noise" and "visual", hence VTOL is preferred with respect to "non-user aesthetics".
- (2) Explicit choice by DM: faced with a small subset of goals, the DM is usually able to evaluate trade-offs and choices mentally, and give an answer. For small, one-shot problems, this is less costly than developing a general formula for the goal variables. Considering fatalities, injuries and property damage predictions, as shown in Figure 3, our DM says VTOL is preferred. The method, if programmed



for computer, would take this information and offer as a check on it the fact that (for a predicted  $3 \times 10^8$  annual passenger miles) 68 lives and 84 injuries are worth more than \$1.4 million. The DM reaffirms his decision on this information, and this trade-off data is stored for future use if needed.

(3) Comparison of intervals: find the interval between the alternatives on each goal, and then decide how these intervals compare with each other. Under the goal "user aesthetics", we find intervals (calculated rail to VTOL) of poor-good on "comfort". We must decide which difference--poor-good on "visual" or excellent-good on "comfort"--is worth more. Assume the latter is the choice: most travelers will probably read rather than look out the window, so the visual aspect is not worth so much. The result is that rail is preferred with respect to "user aesthetics".

(4) Breakpoint on an equivalence measure this technique operates on those intervals that can be expressed quantitatively. Under the goal of "convenience" we place a dollar value on "travel time" (including "delay probabilities") and calculate the breakpoint for the two alternatives. Over the Boston to Washington run, the time savings (VTOL to rail) is an hour and ten minutes, plus an expected delay of five minutes. The cost differential is \$7.00. The breakpoint is then \$5.60 per hour. If a traveler's time is worth more than this, VTOL is preferable; if less, rail (15). Assume that the DM chooses rail.

(5) Modified utility: the two interval-based techniques mentioned just above should be sufficient for most situations. However, there will be times when something even more specific and quantitative is necessary to arrive at a decision. At this point a technique developed by Davidson, Suppes and Siegel<sup>9</sup> can be used to place a rough utility measure over each of the goal variables in question. For value-wise independent goals, a linear weighting of the utilities is a reasonable way to combine.<sup>10</sup> The modification here is the use of a rough utility measure, only well enough defined to allow us to decide, not a completely formulated smooth function. The "socio-economic impacts" goal requires the use of this technique. Rough utility measures are shown in Figure 5. The weights for the three goals are 0.1 for growth patterns, 0.3 for growth rate, and 0.6 for social class impacts. Utility ranges for the predictions in Figure 3 are shown in Table 1.

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<sup>9</sup> A description of this technique can be found in Reference 16.

<sup>10</sup> Value-wise dependent goals cannot be handled this way but must be combined in the goal variables before they can be ranked. For example, "travel time" and "delay probability" were combined by calculating an expected delay time per trip, then adding it to the travel time. The resulting combination was then evaluated.

Table 1. Ranges of Utility on Three Goals

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	Rail	VTOL
Growth Pattern	0.3-0.4	0.5-0.6
Growth Rate	0.6-1.0	0.8-1.0
Social Class	0.75-1.0	0.4-0.75

---

The maximum possible rating for the rail alternative is the weighted sum of the maximum utilities:  $(0.1) \times (0.4) + (0.3) \times (1.0) + (0.6) \times (1.0) = 0.94$ . Similar calculations give the ranges of the two ratings as rail: 0.66 to 0.94; VTOL: 0.53 to 0.81. As there is considerable overlap in the ranges, we need more precise information on the utility measures, and so must use the Davidson, Suppes and Siegel method to gather additional preference data. When this has been done, we can attempt this same procedure again.

The remainder of the example has not been completed. It has served its purpose of illustrating the method. These five techniques can be used to complete the analysis and reach a decision. The solution is not intuitively obvious, nor is it necessarily consistent among different readers. The method allows ample room for subjectivity in choice, but also points out clearly the reasons for the choice.

### III. SUMMARY

The method is designed to guide and assist in the process of choice in complex problems.<sup>11</sup> We assume that several alternatives have been proposed and then proceed to decide among them using the method as follows:

- (1) List the goals.
- (2) Identify all the relations among them: specification, means-end, value-wise dependence and value-wise independence.
- (3) Determine which are the predictable goals; obtain the necessary predictions; convert these predictions into preference statements on each predictable goal.
- (4) Condense this data into a choice, using the framework of the goal fabric and any or all of the following five techniques: dominance check, explicit choice by DM, comparison of intervals, breakpoint on an equivalence measure, and modified utility.

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<sup>11</sup>For an alternative approach, which involves the use of a linear weighting model, see (17).

The principal advantages of this method are as follows:

- (1) It provides a framework for rationality in the solution of complex problems.
- (2) It is a dynamic method, able to adapt easily to additional or revised goals: they can be fitted into the goal fabric and will entail revision of only a few of the evaluation and condensation procedures.
- (3) The method is very flexible and can permit a high degree of direct DM participation, or can use previously gathered preference data to indicate consistent choices without the DM's participation.

There is much work still to be done to perfect and automate this method, but at this stage of development it looks promising.

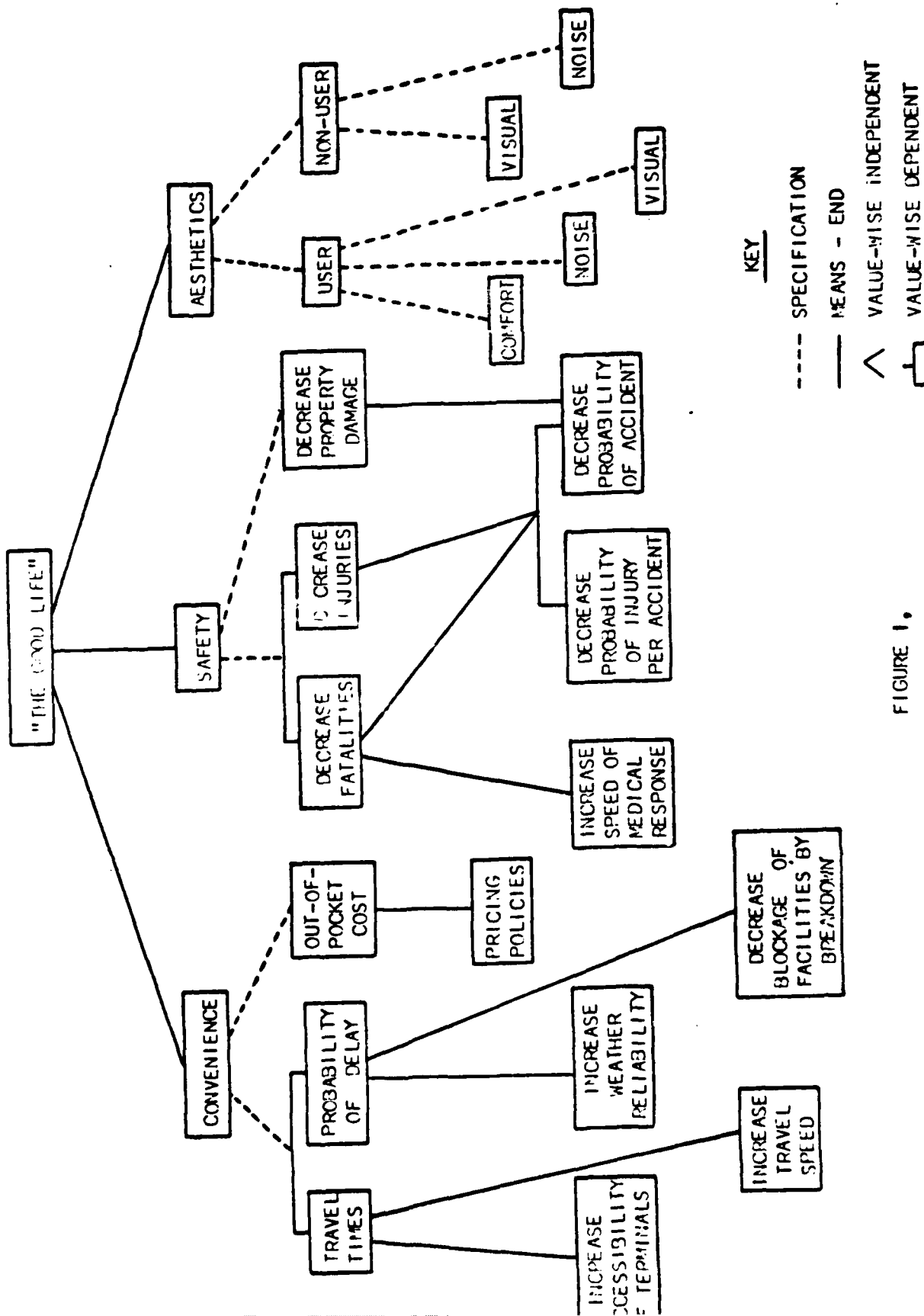


FIGURE 1.

RESULTS OF THE GOAL FABRIC ANALYSIS - PART I

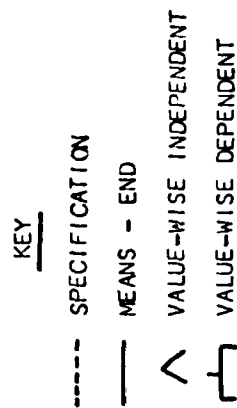
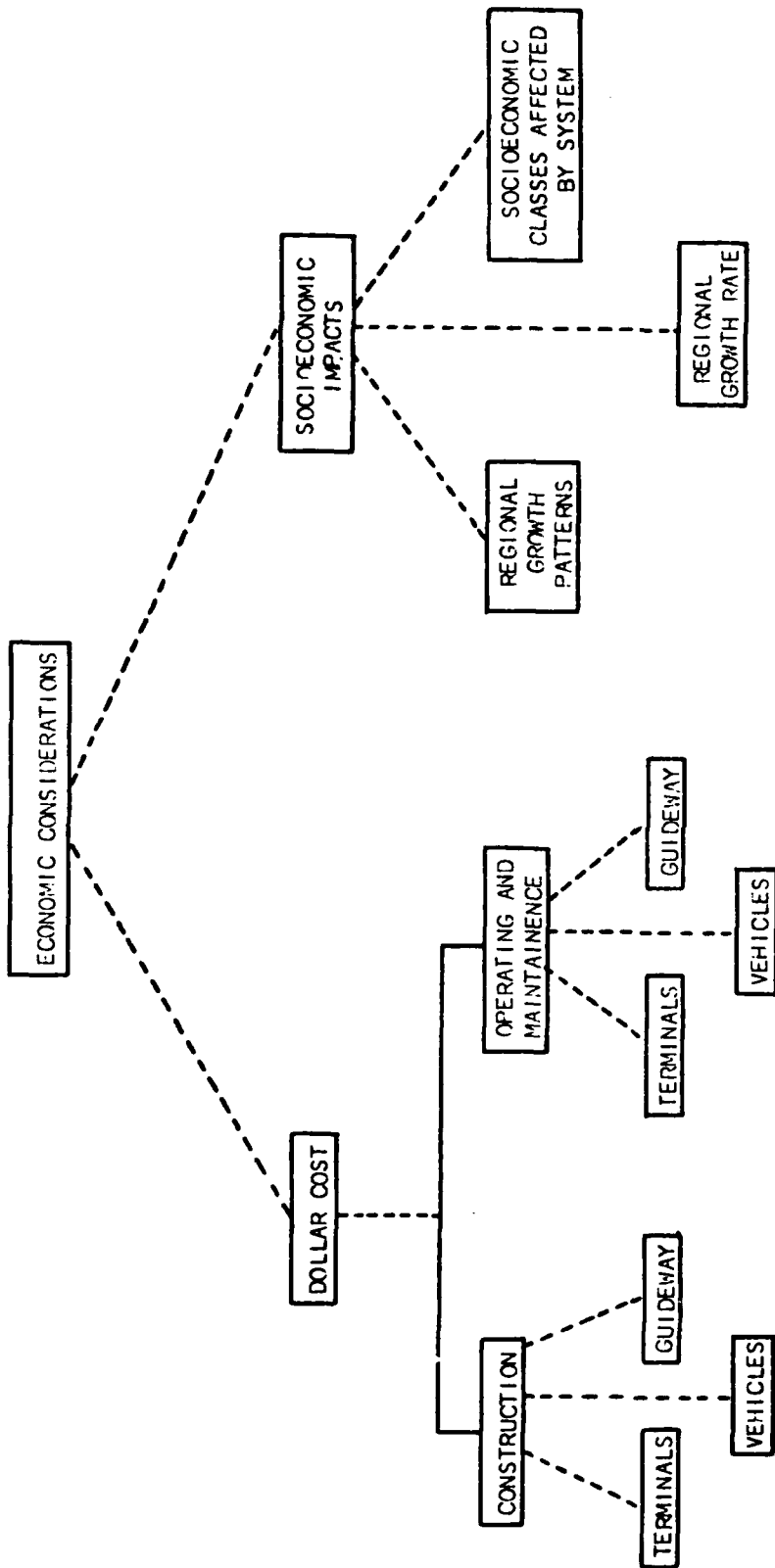


FIGURE 2.  
RESULTS OF THE GOAL FABRIC ANALYSIS - PART II

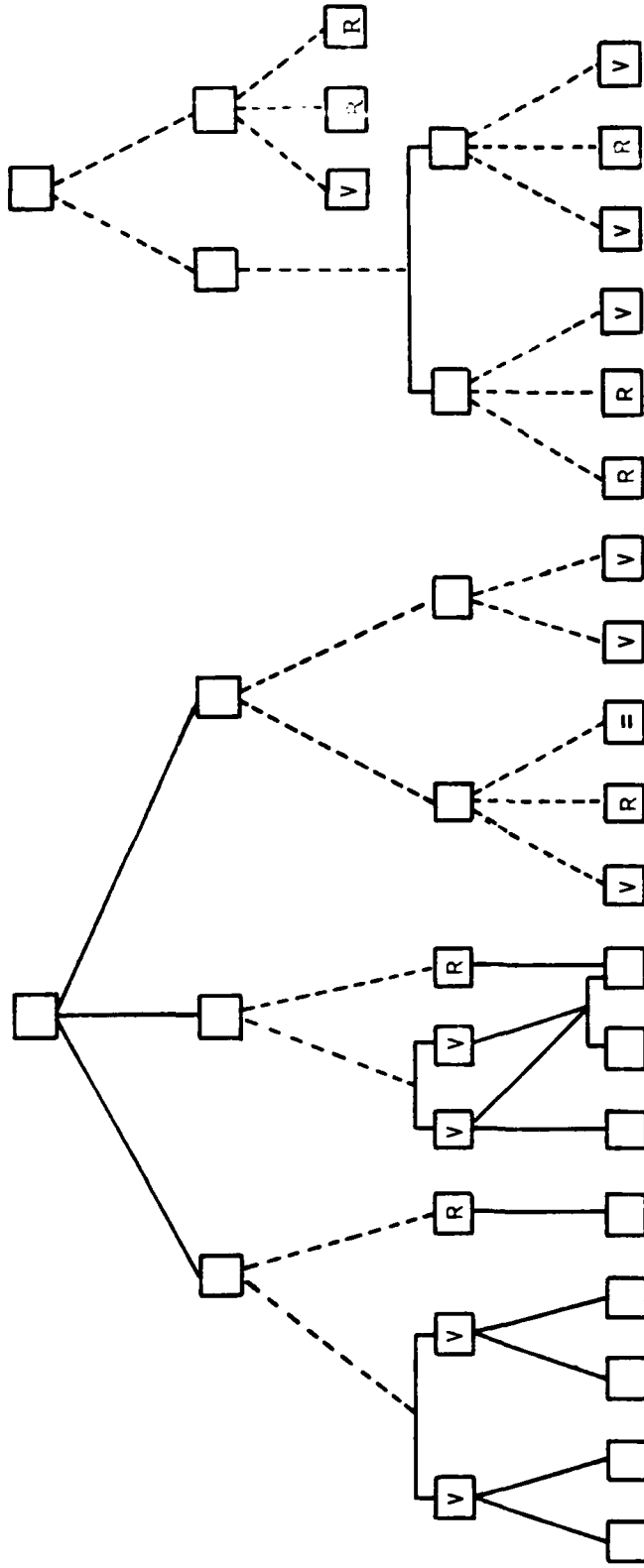
PREDICTABLE GOAL	MEASURE	PAIL	VFOL
Travel times (door to door)	Hours; Wash., D.C.-Boston Phila.-N.Y.C.	3:30 1:20	2:20 1:20
Probability of delay	Percent; bad delay slight delay	0.5% 3.0%	0.0% 1.0%
Out-of-pocket cost (door to door)	Dollars: Wash., D.C.-Boston Phila.-N.Y.C.	\$36. \$12.	\$43. \$14.
Fatalities	Per million passenger-miles	0.26	0.03
Non-fatal injuries	Per million passenger-miles	0.35	0.11
Property damage	\$ per year	$2.6 \times 10^5$	$4.0 \times 10^6$
User comfort	Subjective impression of comfort of ride	excellent	good
User noise	Subjective impression of noise inside vehicle	good	good
User visual	Subjective impression of view from vehicle	poor	good
Non-user visual	Subjective impression of appearance of system	poor	good
Non-user noise	Subjective impression of noise of system	poor	good
Terminal construction cost	\$ per year; 25 year life	$1.6 \times 10^6$	$2.4 \times 10^6$
Vehicle construction cost	\$ per year; 15 year life	$5.3 \times 10^6$	$33.0 \times 10^6$
Guideway construction cost	\$ per year; 25 year life	$36.0 \times 10^6$	0
Terminal operating cost	\$ per year	$2.5 \times 10^6$	$2.0 \times 10^6$
Vehicles operating cost	\$ per year	$100 \times 10^6$	$125 \times 10^6$
Guideway operating cost	\$ per year	$1.0 \times 10^6$	0
Regional growth patterns	Distribution of population density	Restricted; high at nodes	Unlimited; medium at nodes; spread
Regional growth rate	Percent increase in dollar output	5.5	4.0
Socioeconomic classes affected	Class primarily displaced/disturbed by system	Few of any class	Lower middle; few displaced

FIGURE 3.

Predicted Performance of the Alternatives with Respect to the Predictable Goals

Manheim-Hall





# KEY

- R RAIL PREFERRED
- V VTOL PREFERRED
- THE TWO ARE EQUALLY PREFERRED
- SPECIFICATION
- MEANS - END
- △ VALUE-WISE INDEPENDENT
- ┌ VALUE-WISE DEPENDENT

FIGURE 4.

GOAL ENTRY, SHOWING DOMINANCE AT PREDICTABLE LEVELS OF GOALS

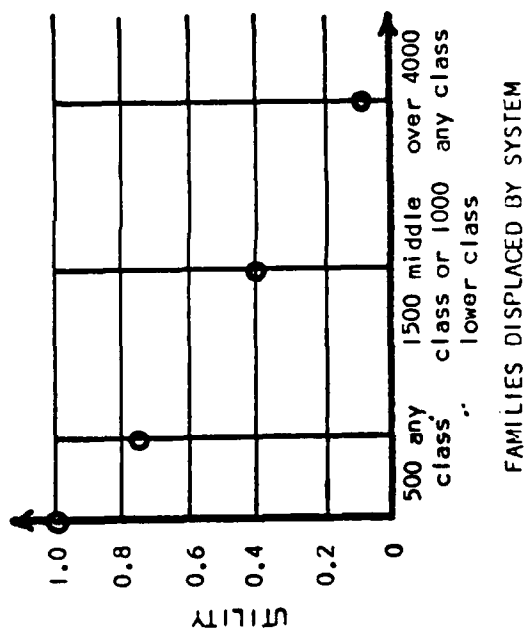
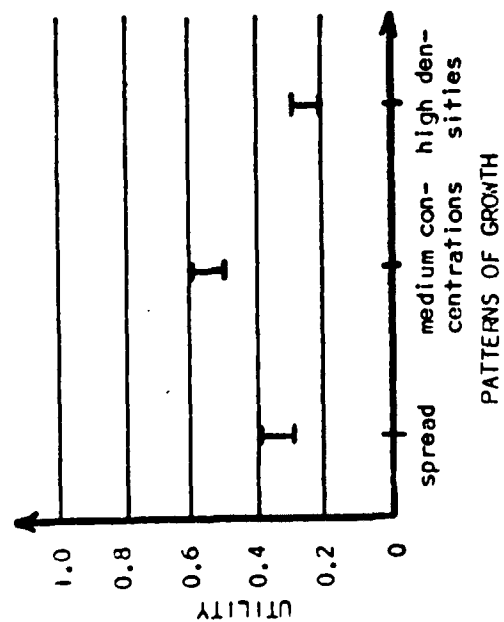
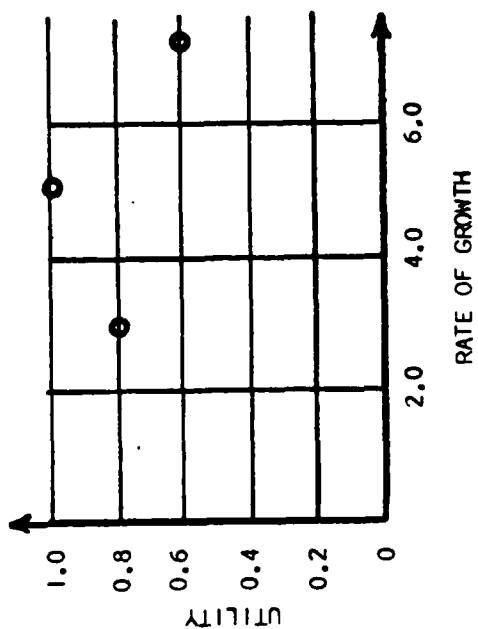


FIGURE 5.  
UTILITY DATA ON THE THREE SOCIOECONOMIC GOALS

### References

1. M. L. Manheim. 1967. Problem-Solving Processes in Planning and Design. Professional Paper P67-3, Department of Civil Engineering, M.I.T., Cambridge, Mass.
2. R. Dorfman, Ed. 1965. Measuring Benefits of Government Investments. The Brookings Institution, Washington, D. C.
3. C. J. Hitch & R. N. McKean. 1965. The Economics of Defense in the Nuclear Age. Atheneum, New York, N. Y.
4. R. D. Luce & H. Raiffa. 1960. John Wiley & Sons, New York, N. Y.
5. J. Von Neumann & O. Morgenstern. 1944. Theory of Games and Economic Behavior. Princeton University Press, Princeton, N. J.
6. M. Hausner. 1954. Multidimensional Utilities. In: Decision Processes, R. M. Thrall, C. H. Coombs & R. L. Davis, Eds. John Wiley & Sons, New York, N. Y.
7. R. M. Thrall. 1954. Applications of Multidimensional Utility Theory. In: Decision Processes, pp. 181-186. R. M. Thrall, C. H. Coombs & R. L. Davis, Eds. John Wiley & Sons, New York, N. Y.
8. Chicago Area Transportation Study, Final Report. 1962. Study conducted under the sponsorship of State of Illinois Department of Public Highways and Buildings, County of Cook, Board of Commissioners of Cook County, and City of Chicago Mayor, in cooperation with U. S. Department of Commerce, Bureau of Public Roads.
9. The Nation's Capital; Policies Plan for the Year 2000. 1961. Prepared by National Capital Planning Commission and National Capital Regional Planning Council. Washington, D. C.
10. H. A. Simon. 1965. Administrative Behavior. Macmillan, New York, N. Y.

11. P. C. Fishburn. 1964. Decision and Value Theory. John Wiley & Sons, New York, N. Y.
12. C. Alexander. 1964. Notes on the Synthesis of Form. Harvard University Press, Cambridge, Mass.
13. C. Alexander. 1965 a & b. A City is not a Tree. Architectural Forum. April, pp. 58-62; May, pp. 58-61.
14. M. L. Manheim. 1966. Hierarchical Structure: A Model of Design and Planning Processes. M. I. T. Press, Cambridge, Mass.
15. M. L. Manheim. 1961. Data Accuracy in Route Location. Traffic Quarterly, January.
16. D. Davidson, P. Suppes & S. Siegal. 1957. Decision Making: An Experimental Approach, Note especially pp. 11-14. Stanford University Press, Stanford, Calif.
17. M. Hill. 1966. A Method for Evaluating Alternative Plans: The Goal-Achievement Matrix Applied to Transportation Plans. Unpublished Ph.D. dissertation, Department of City Planning, University of Pennsylvania.